"Field Test Program to Develop Comprehensive Design, Operating and Cost Data for Mercury Control Systems on Non-Scrubbed Coal-Fired Boilers"

Paper # 24

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ABSTRACT

This paper describes a DOE/NETL program being conducted by ADA-ES that represents the U.S. government's first step toward defining technology platforms for power generating companies to use in meeting new mercury regulations. The Environmental Protection Agency (EPA) announced on Dec. 14, 2000 that they would develop regulations to reduce the emissions of mercury from coal-fired power plants.

Under the contract, ADA-ES will work in partnership with PG&E National Energy Group, Wisconsin Electric Power Company, Alabama Power, and EPRI to design and engineer systems to maximize effectiveness and minimize costs to curtail mercury emissions from power plant flue gases. Reports estimate that mercury control could cost the industry from $2 to $5 billion per year. Much of these costs will be associated with power plants that do not have wet scrubbers as part of their air pollution control configurations. The four plants that will be evaluated during the ADA-ES program are typical of this type of application which is found at 75% of the nearly 1100 units that would be impacted by new regulations.

INTRODUCTION

On December 14, 2000 the Environmental Protection Agency announced that they plan to develop regulations to reduce mercury emissions from coal-fired utility boilers. This decision is based on growing health effects concerns over current levels and potential buildups of methylmercury in lakes and rivers. Methylmercury is capable of bioaccumulation resulting in higher levels in game fish. Mercury is a neurotoxin that impacts rapidly developing cells, so that the greatest risks of exposure are the fetuses of pregnant women who consume fish with elevated levels of mercury. The levels currently being found in lakes in several areas of the country are sufficiently high that state health agencies are issuing advisories to restrict fish consumption.

Over the past ten years, much effort has been directed at reducing the use of mercury in consumer products. In addition, new emission control technologies have been

implemented on medical waste and municipal waste incinerators. As a result, coal-fired electric generators now represent the largest single source of anthropogenic mercury emissions in the US.

In anticipation of potential regulations, a great deal of research has been conducted during the past decade to characterize the emissions and control of mercury compounds from the combustion of coal. Much of this research was the result of funding from the Department of Energy, EPA, and EPRI and are summarized in the comprehensive AWMA Critical Review Article (Brown et al., 1999).

PROGRAM OBJECTIVES

With regulations rapidly approaching, it is important to concentrate the development effort on the most mature control technologies. Injection of dry sorbents such as activated carbon into the flue gas and further collection of the sorbent by conventional particulate control devices, electrostatic precipitators (ESPs) and fabric filters, represents the most mature and potentially most cost-effective control technology for power companies. However, all of the work to date has been limited to bench-scale and pilot experiments (Haythornthwaite et al., 1997; Sjostrom et al., 1997). Although these reduced-scale programs provide valuable insight into many important issues, they cannot fully account for impacts of additional control technology on plant-wide equipment. For example, it has been possible to measure high mercury capture at relatively low temperatures in small pilot systems for relatively short periods. However, these lower temperatures may not be practically achieved in a full-scale system continuously without deposition and corrosion in cold spots of ducting and particulate control equipment.

Therefore, it is necessary to scale up the technology and perform full-scale field tests to document actual performance levels and determine accurate cost information. The objectives of this program are to:

- accelerate the scale-up and availability of commercial mercury control systems for coal-fired plants;
- obtain data on operability, maintainability, and reliability;
- determine maximum mercury removal for various plant configurations; and
- determine the total costs associated with mercury control as a function of fuel and plant characteristics.

This multifaceted field-test program will provide critical data that will be used by many different groups. It will provide EPA with accurate information on the levels of control that can be reasonably attained for different plants. It will complement the emission inventory data obtained during the 1999 ICR data collection effort. Cost and operating data will provide power-generating companies with the means to estimate costs for various plants to perform strategic planning on a system-wide basis. The economic analysis will include:

- Capital costs;
- Sorbent usage costs;
- Impact on operation of particulate control equipment;
- Balance of plant;
- Waste disposal and byproduct utilization issues;
- Enhancements, such as cooling; and
- O&M requirements.

TEAM MEMBERS

ADA-ES has assembled a program team consisting of technical leaders in the areas of mercury measurement, transformations during coal combustion, capture by existing emission-control equipment as well as the design of integrated emission-control systems. Qualifications of individual team members were built by performing pioneering mercury control work in the U.S. over the past decade. Organizations represented on the team include URS Radian, Physical Sciences, Apogee Scientific, EPRI, Energy & Environmental Strategies, EnviroCare, Microbeam Technologies, EERC, Environmental Elements Corp., Consol, Hamon Research Cottrell, and NORIT Americas.

TEST SITES

This program is directed at providing sufficient data to determine costs and capabilities for plants that do not have flue gas desulfurization (FGD) systems. This group represents not only the largest proportion of coal-fired power generators (83% by number or 75% by generation capacity), it also represents the most difficult application for mercury control.

To gather data on the application of sorbent injection for removal of mercury from coal combustion flue gas that can be used for as many plants as possible, sites were selected to take into account factors related to the fuel characteristics, the operating conditions of the unit, and interactions with other air pollution control devices. Sites that burn both Eastern bituminous and Western subbituminous coals were included because of differences in speciation of mercury in the flue gas, which greatly affects the efficiency of mercury removal in air pollution control devices. Measurements of the concentration of mercury species taken in the stacks of pilot and full-scale coal combustion systems reported anywhere from 10% Hg^0 to 95% Hg^0 upstream of the air pollution control device (APCD) (Brown et al., 1999). Oxidized mercury, particularly when present as $HgCl_2$, is far easier to capture than is mercury in elemental (Hg^0) form.

In addition to differences in the forms of mercury produced by different coals, the fly ash produced by bituminous and subbituminous coals result in different mercury capture characteristics. For example subbituminous ashes produce higher absorption rates of mercury at higher temperatures and lower LOI values than do ashes from bituminous coals.

There are other important differences between the flue gas produced by Eastern and Western coals. For Eastern bituminous coals a small proportion, 2 to 3%, of the SO_2 is converted to sulfur trioxide (SO_3). SO_3 is important because it reacts with the water vapor to form sulfuric acid. The gas stream for a low-sulfur eastern coal will have sufficient SO_3 that sulfuric acid will begin to condense at 270°F. This means that the gas stream cannot be cooled for enhancement of mercury capture without first eliminating the SO_3 or else severe corrosion of ducting and ESP components would be expected. On the other hand, the higher alkali content of a Western subbituminous coal neutralizes all of the SO_3 resulting in a dew point of 120°F. This means that a flue gas cooling system could be operated without sulfuric acid corrosion. If an SO_3 injection system is used to control particle resistivity in the ESP, its operation must be integrated with the gas cooling system to provide both resistivity control without causing corrosion problems.

Although fabric filters represent only 10% of the current power plant applications, they are an important part of the program because the number of fabric filters could increase significantly as a result of mercury control regulations. If a high level of mercury removal is mandated, a baghouse may be the most economical choice. Meserole (1999) predicts that achieving 80% removal at a plant with an ESP would require 10 times the amount of sorbent as that required if a fabric filter were installed. The difference in the cost of the additional sorbent would be greater than the annualized cost of a new fabric filter.

Figure 1 shows a plot of the distribution of the specific collection areas (SCA) of ESPs for coal-fired boilers. This shows that there is a large number of smaller ESPs (i.e. < 250 ft^2/kacfm) that would have difficulty handling the additional burden of collecting injected sorbent. Therefore, we decided to include a COHPAC baghouse in the test program because COHPAC represents a cost-effective retrofit option for power plants with ESPs. COHPAC is an EPRI-patented concept that places a high air-to-cloth ratio baghouse downstream of an existing ESP to improve overall particulate collection efficiency. Dry sorbents can be injected upstream of COHPAC, downstream of the ESP. The advantages of this configuration are:

- Sorbents are mixed with a small fraction of the ash (nominally 1%) which reduces the impact on ash reuse and waste disposal.
- Sorbent requirements are reduced by a factor of ten relative to the existing ESP
- Capital costs for COHPAC are less than other options such as replacing the ESP with a baghouse or larger ESP.

Table 1 shows a summary of the four power plants that are participating in the field test program. These four plants provide a means to document the performance of mercury control technology for both subbituminous Powder River Basin (PRB) coals and low-sulfur bituminous coals. Three of the plants have ESPs while the fourth plant has both a hot-side ESP and a COHPAC baghouse. This table also presents the expected timing for the four full-scale tests. This schedule was set up to avoid testing either during the summer peak generation season and harsh winter conditions. Table 2 presents data on

mercury emissions from three of the four plants as determined during the ICR testing. Additional details on the four plants are provided below.

Figure 1. Population Density of ESPs as a Function of SCAs.

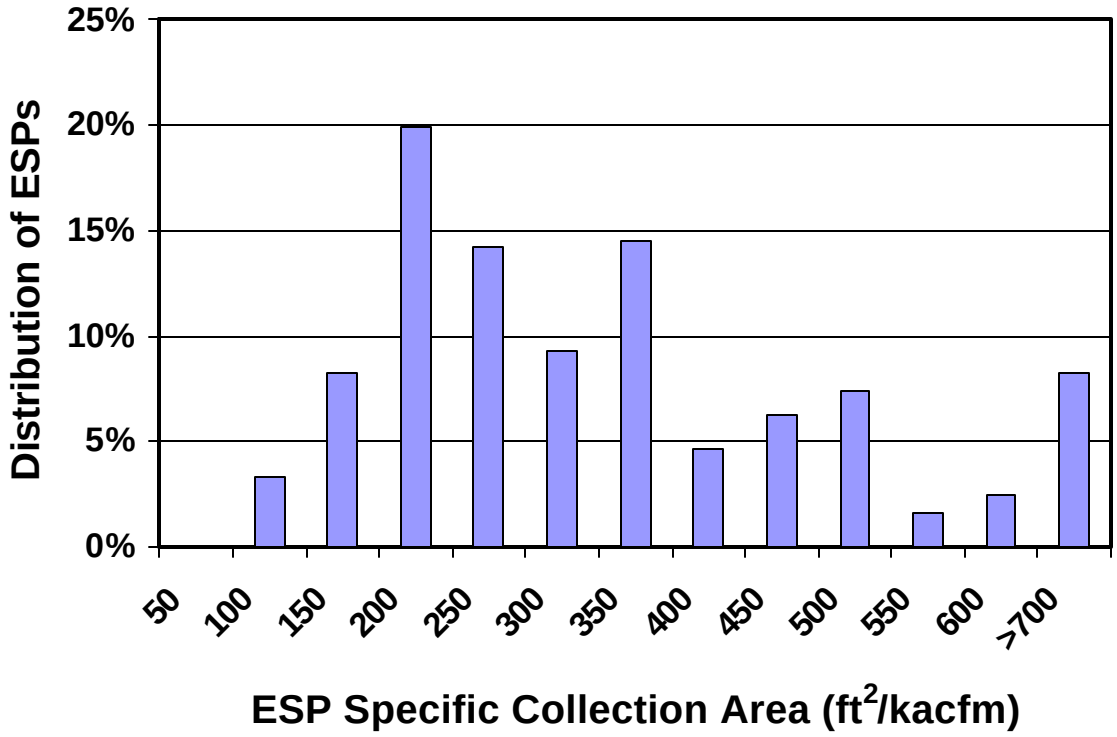


Table 1. Host site for the Mercury Control Field Test Program

Test Site	Coal	Particulate Control	Field Test Schedule
Alabama Power Gaston	Low S. Bituminous	Hot Side ESP COHPAC FF	Spring 2001
Wisconsin Electric Pleasant Prairie	PRB	Cold Side ESP	Fall 2001
PG&E NEG Salem Harbor	Low S. Bituminous	Cold Side ESP	Spring 2002
PG&E NEG Brayton Point	Low S. Bituminous	Cold Side ESP	Fall 2002

Table 2. Mercury Emissions Data on Three Host Sites.

Plant and Unit Sampling Location	Particle Bound	Oxidized, Hg^{2+}	Elemental, Hg^0	Total, Hg
Brayton Point U3				
Inlet (µg/dscm)	1.58	2.53	1.18	5.3
Outlet (µg/dscm)	0.39	2.09	1.19	3.67
Removal Efficiency (%)	76.46	-16.93	-3.25	31.92
Salem Harbor U3				
Inlet (µg/dscm)	2.83	0.10	0.29	3.22
Outlet (µg/dscm)	0.0554	0.0925	0.2501	0.3980
Removal Efficiency (%)	97.96	-23.07	8.39	87.28
Gaston U1[a]				
Inlet (µg/dscm)	2.26	1.72	2.81	6.80
Outlet (µg/dscm)	0.60	3.99	2.06	6.65
Removal Efficiency (%)	73.45	--131.98	26.69	2.21

a. Measurements made across hot-side ESP not COHPAC baghouse.

Alabama Power E.C. Gaston Unit 3 is a 270 MW B&W wall-fired boiler that burns a washed Alabama bituminous coal. The coal has a heating value of 13,700 BTU/lb and a mercury content of 0.06 µg/g and 0.03% chlorine. Particulate is captured by a Research Cottrell hot-side weighted-wire ESP with an SCA of 274 ft^2/kacfm. This is followed by a Hamon Research Cottrell COHPAC baghouse designed with an air-to-cloth ratio of 8.5:1 gross. The temperature of the baghouse ranges from 240-300 ^oF. During the test program the sorbent will be injected downstream of the ESP and air preheater and upstream of the baghouse.

Wisconsin Electric Pleasant Prairie Power Plant Unit 2 is a 600 MW Riley Stoker balanced draft, turbo-fired boiler that burns PRB coal. The coal has a heating value of 11,897 BTU/lb with mercury content of 0.1 µg/g and 0.0015% chlorine. Particulate is captured by a Research Cottrell cold-side weighted wire ESP with an SCA of 468 ft^2/kacfm. A WAHLCO SO_3 system is used to condition the flyash. The unit operates in a temperature range of 280-310 ^oF.

PG&E National Energy Group (NEG) Salem Harbor Unit 1 is an 85 MW B&W Radiant boiler that fires a South American bituminous coal. The coal has a heating value of 11,300 BTU/lb with mercury content of 0.03µg/g and 0.03% chlorine. Particulate is captured by an Environmental Elements cold-side rigid-electrode ESP with an SCA of 474 ft^2/kacfm. A FuelTech urea-based SNCR system is used to control NO_x levels. The ESP operates at temperatures as low as 250 ^oF.

PG&E NEG Brayton Point Unit 1 is a 250 MW CE tangential, twin furnace boiler burning a low-sulfur eastern bituminous coal. The coal has a heating value of 12,319 BTU/lb with mercury content of 0.05 µg/g and 0.08% chlorine. A pair of ESPs in series captures particulate. The first is a Koppers weighted-wire cold-side ESP with an SCA of 156 ft^2/kacfm. The second unit is a Research Cottrell rigid-electrode ESP with an SCA

of 403 ft^2/kacfm. An EPRICON SO_3 system is used to condition the flyash. The plant uses Separations Technology equipment to process the collected flyash by electrostatically separating LOI carbon from the flyash (Giovando, 2000).

SORBENT SELECTION AND SCREENING

The test program at each site allows for the evaluation of two sorbents including a lignite-derived activated carbon supplied by NORIT, referred to as Darco FGD carbon, and one alternative sorbent. FGD is considered the benchmark for these tests because of its wide use in DOE/EPRI/EPA sponsored testing. Because of the economic impact of sorbent cost on the overall cost of mercury control, it is desirable to find less expensive sorbents such as flyash-derived products or a less expensive form of activated carbon. A sorbent selection criteria has been developed so that sorbent vendors/developers can clearly understand the needs and requirements of this program. In summary an alternative sorbent must:

- Be at least 25% less expensive than FGD carbon;
- Be available in quantities of at least 15,000 lbs, and potentially as high as 250,000 lbs. for site tests;
- Be available in sufficient quantities to supply at least 100,000 tons per year by 2007; and
- Have a capacity of at least 100 μg/g as measured in the laboratory by URS Corporation.

Sorbents will be tested on a slipstream of flue gas for site-specific mercury capacity using URS Corporations' fixed bed mercury absorption device. This device was developed with funding from EPRI and has been used to screen dozens of sorbents. Adsorption tests are conducted by saturating sorbents with either elemental mercury or mercuric chloride in the presence of simulated flue gas. The test apparatus is illustrated in Figure 2. In the laboratory, simulated flue gas is prepared by mixing heated nitrogen gas streams containing SO_2, HCl, NO_x, CO_2, H_2O, and O_2. Mercury is injected into the gas by contacting nitrogen carrier gas with either recrystallized mercuric chloride solids or with an elemental mercury permeation tube (VICI Metronics) housed in a mercury diffusion vessel. Mercury concentration is controlled by the temperature of the diffusion vessel and the nitrogen carrier gas flow rate. During field screening tests, actual flue gas is drawn into the apparatus.

Sorbents are mixed in a sand diluent prior to being packed in a temperature-controlled, adsorption column (1.27 cm ID). A ratio of 20 mg sorbent to 10 g of sand is generally used for carbon-based sorbents and zeolites, and 200 mg sorbent to 10 g of sand was used for fly ashes. These mass-loadings are chosen to achieve reasonable mercury breakthrough times with the respective sorbents. Prior to flue gas exposure, the sorbent fixed-bed is heated to the desired temperature for periods up to one hour. During this time, the flue gas is by-passed directly to the analytical system to determine the "inlet"

mercury concentration. Adsorption tests were initiated by flowing flue gas downward through the fixed-bed column at a flow rate near 1 L/min. Mercury measurements are made with a mercury semi-continuous emissions analyzer (S-CEM) described later in this section.

The amount of mercury exiting the sorbent column is measured on a semi-continuous basis. Gas is passed through the column until 100% of the inlet mercury is detected at the outlet (100% breakthrough). The 100% breakthrough (equilibrium) capacity of the sorbent (µg Hg/g sorbent) is determined by summing the total mercury adsorbed until the time when the outlet mercury concentration is first equal to the inlet concentration.

SEMI-CONTINUOUS EMISSIONS MONITOR

Semi-continuous gaseous mercury analyzers built by Apogee Scientific will be used during this program to provide near real-time feedback during baseline, parametric and long-term testing. Continuous measurement of mercury at the inlet and outlet of the particulate collector is considered a critical component of a field mercury control program where mercury levels fluctuate with boiler operation (temperature, load, etc.) and decisions must be made concerning parameters such as sorbent feed rate and cooling. The analyzers that will be used for this program consist of a commercially available cold vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). A sketch of the system is shown in Figure 3. One analyzer will be placed at the inlet of the particulate collector and one at the outlet of the particulate collector during this test program.

Although it is very difficult to transport non-elemental mercury in sampling lines, elemental mercury can be transported without significant problems. Since the Au-CVAAS measures mercury by using the distinct lines of UV absorption characteristic of elemental Hg (Hg^0), the non-elemental fraction is either converted to elemental mercury (for total mercury measurement) or removed (for measurement of the elemental fraction) near the sample extraction point. This minimizes any losses due to the sampling system.

For total vapor-phase mercury measurements, all non-elemental vapor-phase mercury in the flue gas must be converted to elemental mercury. A reduction solution of stannous chloride in hydrochloric acid is used to convert Hg^{2+} to Hg^0. The solution is mixed as prescribed in the draft Ontario Hydro Method for manual mercury measurements.

Figure 2. Bench –Scale, Fixed-Bed Mercury Adsorption

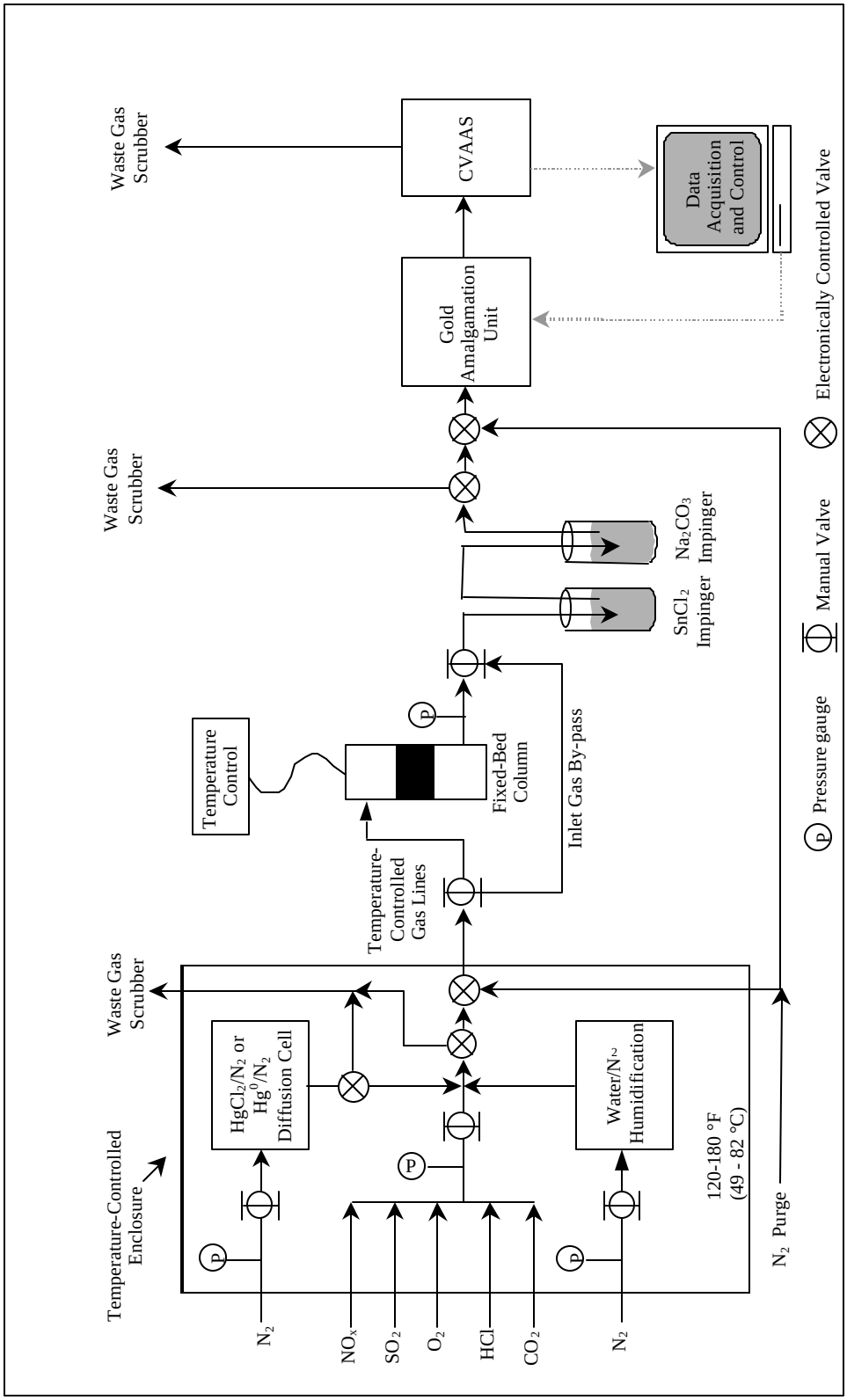
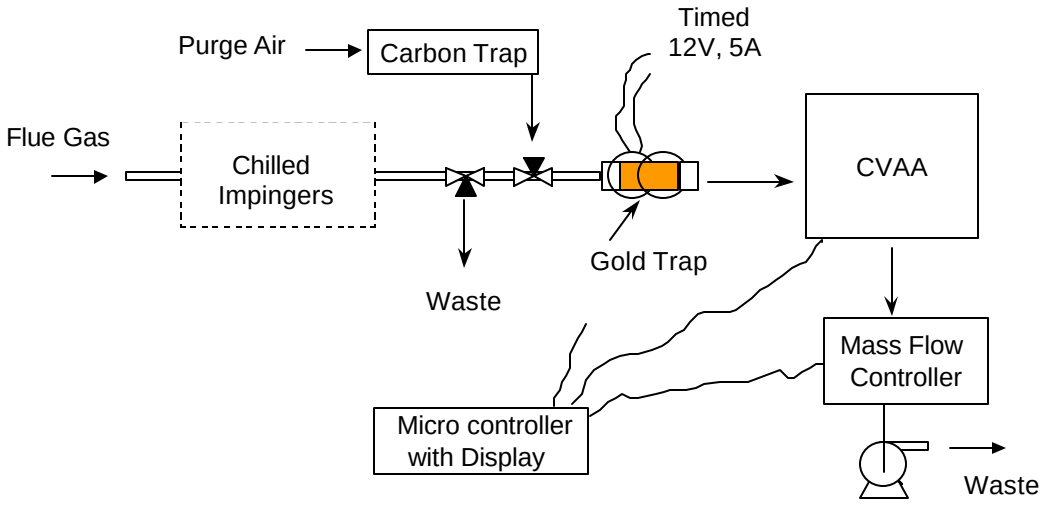


Figure 3. Sketch of Mercury Measurement System.



To measure speciated mercury, an impinger of potassium chloride (KCl) solution mixed as prescribed by the draft Ontario Hydro Method is placed upstream of the stannous chloride solution to capture oxidized mercury. Unique to this instrument is the ability to continuously refresh the impinger solutions to assure continuous exposure of the gas to active chemicals. The Au-CVAAS system is calibrated using elemental mercury vapor. The instrument is calibrated by injecting a metered volume of mercury-laden air from the air-space of a vial containing liquid mercury at a precisely measured temperature into the analyzer.

The Au-CVAAS can measure mercury over a wide range of concentrations. Since the detection limit of the analyzer is a function of only the quantity of mercury on the gold wire and not the concentration in the gas, the sampling time can be adjusted for different situations. Laboratory tests with stable permeation tube mercury sources and standard mercury solutions indicate that the noise level for this analyzer is 0.2 ng mercury. To sample at 50 – 100 times the noise level during field testing, the sampling time is set so at least 10 ng mercury is collected on the wire before desorption. Table 3 shows the sampling time required for different concentrations of mercury in the flue gas with 2 liters per minute sample flow.

Table 3. Sampling Time Required for Au-CVAA Analyzer.

VAPOR-PHASE MERCURY CONCENTRATION ($\mu g/M^3$)	MINIMUM SAMPLE TIME (MIN)	NOISE LEVEL ($\mu g/M^3$)
5	1	0.1
2.5	2	0.05
1	5	0.02
0.5	10	0.01

Particulate is separated from the gas sample using a self-cleaning inertial gas separation arrangement modified for use with this mercury analyzer under an EPRI mercury control program. This arrangement uses a system where excess sample flow continuously scours particulate from a secondary filter so as to minimize any mercury removal or conversion due to the presence of particulate.

SORBENT INJECTION EQUIPMENT

The sorbent injection equipment is a skid mounted, portable dilute phase pneumatic system. The activated carbon will be delivered to the plant in 900-lb supersacks, which will be stored on pallets adjacent to the injection skid. Operators will load individual supersacks onto the injection skid by a hoist. The reagent is metered by a variable speed screw feeder into an eductor that provides the motive force to carry the reagent to the injection point. A positive displacement blower provides the conveying air. A PLC system is used to control system operation and adjust injection rates. Flexible hose will carry the reagent from the feeder to a distribution manifold located upstream of the particulate collector feeding multiple injection probes inserted into the duct to distribute the sorbent evenly across the flue gas.

FIELD TESTING

Prior to installing injection equipment, preliminary system operation, performance and mercury level measurements will be made. Mercury will be measured using the S-CEM across the particulate control device. These measurements will be used to expedite the parametric evaluation and provide insight as to current mercury removal efficiencies during "normal" operation with varying boiler load. During this test, the S-CEM will be run continuously for a minimum of 24 hours at each site. These data will be used to design the parametric tests with the minimum number of uncontrolled variables.

After installation of the sorbent injection equipment, a second set of baseline tests will be conducted to fully document baseline conditions. During this test boiler load will be held steady at "full-load" conditions during testing hours, nominally 7:00 am to 7:00 p.m. Mercury levels across the particulate control device will be measured using two separate methods: 1) the S-CEM; and 2) standard Ontario Hydro Testing. This baseline test is expected to run for one week.

Following the baseline test, a parametric series of tests will be conducted to document mercury removal levels as a function of injection rate and gas temperature. The flue gas temperature will be lowered at each condition to document the effect of 10 - 20^{o}F decrease in temperature on mercury removal efficiencies. The maximum sorbent injection rate will be established by either a 90% mercury removal level or a sorbent feed proportional to 30 lb/Macf which is considered an economic maximum. The sorbent injection rates to achieve different removal rates will be set with feedback from the S-CEM.

The next series of parametric tests will be conducted using an alternative sorbent. Mercury removal as a function of injection rate will be measured at the optimum

temperature measured during the previous test series. After this test the field crew will leave the site to analyze data and work with team members on establishing conditions for the long-term test.

The final test will be a mercury removal validation program conducted for a maximum of fourteen days at the "optimum" plant operating conditions (lowest cost/highest mercury removal) as determined from the parametric tests. The S-CEM will be used for continuous monitoring of mercury removal. Ontario Hydro measurements at the inlet and outlet will be conducted.

WASTE CHARACTERIZATION

During each field test program, samples of the ash/sorbent mixture from the hoppers will be collected and analyzed. The standard testing technique used for assessing hazardous waste characteristics is the Toxicity Characteristic Leaching Procedure (TCLP, SW846-1311). A 100-gram sample of ash is exposed to 1-liter of acidic solution (acetic acid-or acetate based) for 24 hours. The solution is then analyzed for several metals (including mercury) to determine how much of each target metal was leached from the solid sample. Results are compared against limits established by regulation. In the case of mercury, a maximum leachable level of 0.2 mg/liter has been established.

A second series of tests will be performed to answer the question of the stability of the mercury. The potential long-term environmental impact of the mercury-laden ash will be determined using two techniques, leaching and thermal desorption. The Energy and Environmental Research Center (EERC) will conduct these tests. Leaching tests are done using a method known as the synthetic groundwater leaching procedure (SGLP) (Hassett, et al., 1999). This test is modeled after the TCLP, but modified to allow for disposal scenarios. A shake extraction technique is used to mix the solid sample with an aqueous solution. Aliquots of the liquid are then analyzed after 18 hours, 2 weeks, and 4 weeks. Thermal desorption tests will be performed using a special test fixture that is heated using a programmable temperature controller. The temperature of the ash sample is ramped to 500 ^{o}C at a rate of 20 ^{o}C per minute. Mercury that is released by the sample is swept to a spectrophotometer for mercury measurement as a function of time and temperature.

DESIGN AND ECONOMICS OF SITE SPECIFIC CONTROL SYSTEM

After completion of testing and analysis of the field data, the requirements and costs for full-scale, permanent commercial implementation of the necessary equipment for mercury control using sorbent injection technology will be determined. Process equipment shall be sized and designed based on test results and the plant specific requirements (reagent storage capacity, plant arrangement, retrofit issues, winterization, controls interface, etc.). A conceptual design document shall be developed with drawings and equipment lists. Modifications to existing plant equipment shall be determined and a work scope document developed based on input from the plant which may include modifications to the particulate collector, ash handling system, compressed air supply, electric power capacity, other plant auxiliary equipment, utilities and other balance of

plant engineering requirements. Reagent type and sources shall be evaluated to determine the most cost -effective reagent(s) for the site.

TECHNOLOGY TRANSFER

Transferring the information generated during this program to the coal-fired power generation industry will be an important part of the program. This will be accomplished through technical papers presented at various forums including AWMA annual meeting, ICAC meetings, AWMA Specialty Conferences on mercury, and the EPRI/DOE/EPA MEGA Symposium. In addition, results from the test programs will be made available to the public as soon as they are completed and approved by DOE and the host power generating companies. We will use the ADA-ES website (www.adaes.com) to distribute these reports.

ACKNOWLEDGEMENTS

This large-scale test program could not be conducted without technical and administrative support from a large number of people at the various power-generating companies. We would like to acknowledge all of these individuals and especially the following key personnel: Dr. Larry Monroe of Southern Company Services, Mr. Herb Stowe of PG&E NEG, and Mr. Dick Johnson of Wisconsin Electric. We also acknowledge the valuable input being provided by Dr. Ramsay Chang of EPRI and Mr. James Kilgroe of EPA.

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